CHAPTER 10

THE TRIUMPH OF QUANTUM FIELD THEORY

In this chapter we present an overview of Quantum Field Theory. We will describe its structure and some of its many successes. Also, out of fairness, we will describe the gaps in the theory. But first we will start with the three pillars on which this amazing edifice rests, as presented by Julian Schwinger in his lectures at Harvard University in 1956-59.

THE PILLARS

The field principle. The first pillar is the assumption that nature is made of fields. A field is a set of physical properties that exist at every point of space. However, the concept of a field as a property of space does not come easily. It eluded the great Newton, even though he couldn't accept action-at-a-distance. It wasn't until 1845 that Faraday, inspired by patterns of iron filings, conceived the idea of fields, and it took another 50 years before the concept was accepted without invoking an imaginary ether. QFT comprises seven fields — five force fields and two matter fields.[1] The force fields include gravity, electromagnetic forces, strong and weak nuclear forces, and the recently-discovered Higgs field. The matter fields include lepton and baryon fields. Two of these fields — strong and baryon — are *effective* fields that are made of more basic but "invisible" fields called quarks and gluons. The use of colors is my attempt to make the field picture more palatable.

The relativity principle. The second pillar is the assumption that the field equations are the same for all uniformly-moving observers. This is Einstein's Principle of Relativity, famously enunciated in 1905. QFT is the only theory that successfully combines the relativity and quantum principles.

The quantum principle (discretization). The quantum principle was introduced in 1900 by Max Planck, who showed that EM radiation emitted by hot objects consists of discrete chunks that he called quanta (Chapter 3). Discretization was demonstrated experimentally in 1922 by Otto Stern and Walther Gerlach. Their classic experiment showed that the angular momentum (or spin) of the electron can have only two values — nothing in between (Fig. 10-1). In Schwinger's QFT all physical properties are treated as discrete (S2001). Even field strengths, whose values are continuous, are treated mathematically as the limit of increasingly finer discrete values. It is discretization that leads to the use of Hilbert algebra as the language of QFT.

Fig. 10-1. The Stern-Gerlach experiment. A beam of atoms is deflected when it enters a non-uniform magnetic field. Classically one would expect that the atom's magnetism (which arises from the spin of its electrons) could have any magnitude and that the beam would be deflected into a continuous band. Instead, the beam separates into two distinct parts as shown, corresponding to discrete spin values of +½ and -½ in Planck units. (www.upscale.utoronto.ca)

Occam's Razor. I'm tempted to add another principle, but it's really more of a wish than a rule. I'm referring to Occam's razor, which states in essence that all other things being equal, the simplest explanation is the best. Einstein put it somewhat differently: "A physical theory should be as simple as possible, but no simpler." The last phrase is important because, as Schwinger said, "nature does not always select what we, in our ignorance, would judge to be the most symmetrical and harmonious possibility". If the theory were as simple as possible, there would be just one field (or perhaps none!), and the world would be very uninteresting — not to mention uninhabitable. I think it can be said that the equations of QFT are indeed about as simple as possible, but no simpler.

> **The move from a particle description to a field description will be especially fruitful if the fields obey simple equations, so that we can calculate the future values of fields from the values they have now… Maxwell's theory of electromagnetism, general relativity, and quantum chromodynamics all have this property. Evidently, Nature has taken the opportunity to keep things relatively simple by using fields. – F. Wilczek (W2008, p. 86)**

THE EDIFICE

On these pillars rests the most successful theory ever constructed. Except for a few gaps, this theory explains everything from the tiniest atomic nucleus to the most remote star. Not only that, but most of the explanations emerge from the theory as easily and naturally as raindrops falling from the clouds, or better yet, like presents appearing under the Christmas tree. Following are some of the more attractive and accessible of these presents. Some have already been mentioned and some will be pleasant surprises.

Quanta. Quantum fields exist in three different forms: quanta, self-fields, and vacuum fields. A quantum is a separate, indivisible chunk of field that lives a life and dies a death of its own. For example, the photon is a quantum of the EM field, and protons and neutrons are quanta of the baryon field. Quanta are sometimes called *excitations* in a field, but that term doesn't do them justice. Excitations can have any magnitude and can diminish as they travel and slowly die away like water waves, whereas quanta are indivisible and act as a unit. They may be free and travel through space on their own, or they may be bound, as an electron in an atom, but each quantum keeps its own identity. If it is absorbed or changes its spin state, it does so as a unit. Because of this all-or-nothing behavior, quanta act like particles, making it difficult for many physicists to give up their belief in particles.

Self-fields. Self-fields do not have a life of their own; they are created by a source and are permanently attached to that source (see Fig. 3-1). Examples of self-fields are the gravitational field of the earth, the electric field around an electron or proton, and the strong and weak fields around a nucleon.

The vacuum field. Finally, there is the vacuum field. The equations of quantum field theory do not permit the field strength ever to be zero. Even in regions where there are no quanta or self-fields, there is a background field called the vacuum field. The vacuum field is especially important in the case of the Higgs mechanism (see below).

Hilbert algebra. Quantum fields are not described by simple numbers. They are described by vectors in what mathematicians call *Hilbert space* and their dynamics are described by *operators* that obey partial differential equations. Thus, while classical field intensity is described by a simple number in QFT we talk about the expectation value of field intensity. However, since my aim is to avoid mathematics, I will not go into this any further. You do not need to

understand Hilbert algebra, or even to know the field equations, to grasp the basic concepts of QFT. Just remember that Hilbert space is not real; it is a mathematical tool and is not to be confused with the physical fields that exist in real three-dimensional space.

Mass. In classical physics mass is a measure of inertia (see Chap. 2), but in QFT mass is a number that appears in the field equations. The effect of the mass term is to slow down the speed at which a field evolves and propagates, so mass plays the same inertial role in QFT that it does in classical physics. But this is not all that mass does. This same term also causes the fields to oscillate, and the greater the mass, the higher the frequency.[2]

Energy. In classical physics, energy means the ability to do work and work is defined as force exerted over a distance. This definition, however, doesn't provide much of a picture, so in classical physics energy is a rather abstract concept. In QFT, on the other hand, the energy of a quantum is represented by oscillations in its field intensity: the more energy, the faster the oscillations. In fact Planck's famous relationship between energy and oscillation frequency (see Chap. 3) follows directly from the equations of QFT. In our color analogy, we might say that the oscillations cause the color to "shimmer"; the faster the shimmer, the greater the energy of the field.

***e = mc*^{2}**. I know, I promised there would be no equations and, except for a few footnotes, I've kept my promise. But I think you will forgive me for making an exception for the world's most famous equation — the only equation to have its biography written (B2000). And the thing is this: $e = mc^2$ pops right out of QFT. Einstein had to work hard to derive it; it was published in a separate paper that followed his first breakthrough paper on relativity theory in 1905, but in QFT this equation follows as a simple consequence of the two previous results. Since both mass and energy are represented by oscillations in the field intensity, it doesn't take an Einstein to see that there is a relationship between the two. In fact, any schoolboy can combine the two equations and find (big drum roll, please) $e = mc^2$.[3] Not only does this equation tumble right out of QFT, its meaning is seen physically in the oscillations of the fields. (This simple derivation only occurred to me as I was writing this book.)

Field components. Each of the seven fields in QFT is actually a group of interrelated "sub-fields" that share a set of equations. For example, what we call the EM field is a combination of electric and magnetic fields that are described by Maxwell's equations. Another example is the lepton field, which

consists of four component fields to accommodate the two possible spins and charges

Spin (or helicity). In QFT there are no particles, so there is nothing to spin on its axis and the concept of *spin* is not easy to picture. Because of this, the term *helicity* is sometimes used in place of spin. Helicity is a mathematical concept related to the number of field components and how they change when viewed from different angles. Helicity gives rise to angular momentum, just as does a spinning particle.

Exclusion principle. The *exclusion principle* states that two field quanta with half-integer spin (called *fermions* after Enrico Fermi) cannot be in the same quantum state. This explains why matter quanta (electrons, protons, etc.) are seen only as separate entities. It also explains why each electron in an atom must be in a different quantum state (as described in Chapter 6) and why there is a limit to the number of neutrons in an atom (see "A delicate balance" in Chapter 4).

When the exclusion principle was introduced by Wolfgang Pauli in 1925, it was only a guess — an empirical postulate. It is only in QFT that this important principle has a theoretical basis as a consequence of the *spin-statistics theorem*.

> **In my original paper I stressed the circumstance that I was unable to give a logical reason for the exclusion principle or to deduce it from general assumptions… If we search for a theoretical explanation of this law, we must pass to the discussion of relativistic wave mechanics. – W. Pauli (Nobel lecture, 1945)**

Classical limit. The exclusion principle does not apply to force field quanta (called *bosons* after Satyendra Bose), which have integer spin. They can overlap and build up. Even though each quantum acts individually, if there are many present the effect is the same as a classical field.

Quantum collapse. If fields evolved only as described by the field equations, nothing of significance would happen because the equations do not describe the transfer of energy or momentum. For example, they don't describe how a photon transfers its energy to a photoreceptor in your eye. I call this process *quantum collapse* because after a quantum transfers its energy it can't continue to exist; it must disappear from all space. Like Schrödinger's cat, it can't be in a state of half dead and half alive. Even though we have no theory to describe quantum collapse, we know that it happens; indeed, it is an

essential part of QFT.[4] As Art Hobson wrote, referring to the two-slit experiment:

> **The entire spread-out field… must deposit its quantum of energy all at once, in a single instant, because the field cannot carry some fraction of one quantum – it must always contain either exactly one or exactly zero quanta of energy. When the field deposits its quantum of energy on the viewing screen, the entire spread-out field must instantaneously lose this much energy. — A. Hobson (H2007, p. 303)**

Quantum collapse is similar to collapse of the wave-function in QM, but the concepts are very different. In QM the wave-function describes the probability that a particle is in a given place or that the system is in a given state, and when a measurement is made the probabilities "collapse" into a certainty. In QFT the collapse is a *physical process* that actually happens. It may not be what we expected, but neither did we expect that the earth is round or that matter is made of atoms. Just as we learned to live with those concepts, so we can learn to live with quantum collapse.

Not only is quantum collapse a necessary part of QFT, it provides solutions to two of the most vexing problems in physics today: the measurement problem and entanglement, as described in Chapter 9.

Quarks and gluons. Quarks and gluons are the basic fields that constitute the strong and baryon fields, but they do not exist in free form. This is known as the Principle of Confinement. Indeed, we would not have known about them if not for the large number of *hadrons* (quanta of the strong and baryon fields) that were discovered in the latter half of the 20th century – the so-called "subatomic zoo". It was Yuval Ne'eman, an Israeli physicist, and Murray Gell-Mann who saw a pattern in the "zoo" that Gell-Mann dubbed "The Eightfold Way". This pattern led Gell-Mann to predict a new particle (the omega-minus) that was observed in 1963 with the predicted properties. Then in 1964 Gell-Mann and George Zweig showed that this pattern would result if hadrons were made of more basic fields that Gell-Mann (quite the wordsmith) called *quarks*, a word taken from Ulysses by James Joyce.[5] Later *gluons* (again, Gell-Mann's term) were introduced to hold the quarks together. The field theory that describes quarks and gluons was given the name (by guess whom) *quantum chromodynamics* (QCD), because arbitrary colors are used to describe certain properties of the quarks. (These colors are not to be confused with the equally arbitrary colors I have used to help visualize fields.) While

QCD has its own name, it still is part of Quantum Field Theory.

"One of the greatest scientific achievements of all time". In a recent calculation it was shown that the field equations for quarks and gluons account for the mass and spin of all the hadrons in the sub-atomic zoo.[6] The basic parameters of the quark and gluon fields were first determined from three of the known masses. The field equations were then used to calculate stable and quasi-stable excitations of the quark and gluon fields. Fourteen such excitations were found with mass and spin in close agreement with the fourteen known hadrons, ranging from the proton and neutron to the exotic charmonium. Equally important is that there were no excitations corresponding to the quarks and gluons themselves, thereby providing a theoretical basis for the Principle of Confinement. As Frank Wilczek wrote:

> **Through difficult calculations of merciless precision that call upon the full power of modern computer technology, [we have] shown that unbendable equations… account convincingly and in quantitative detail for the existence of protons and neutrons, and for their properties… I believe this is one of the greatest scientific achievements of all time. — F. Wilczek (W2008, p. 122-127)**

An achievement, I might add, that very few people are aware of.

The Higgs field. The Higgs field is the newest field in QFT; its quantum (called the Higgs boson) was detected in 2012. It interacts with all other fields and, because it has a large vacuum expectation value, it generates the effective mass of these fields. It was the final ingredient that made electroweak unification possible (see Chapter 5).

Dark Matter. As early as 1933, astronomical observations showed that there is more matter in the universe than was previously thought. In fact, astronomers now believe that ordinary matter constitutes only about 5% of the total mass of the universe, while something called *dark matter* makes up 27% of the total mass. (The rest is made of a related substance called dark energy, which we won't go into.) This conclusion is based on its apparent gravitational influence on other objects.[7] Dark matter is found primarily around galaxies and is believed to be a million times less dense than normal matter. It is not "seen" because it doesn't emit or absorb light — that is, it doesn't interact (or interacts very feebly) with the EM field.

QFT offers two possible explanations for dark matter. One possibility is a field suggested by Steven Weinberg and Frank Wilczek, with quanta called

axions. Attempts have been made to detect axions with an apparatus called DAMA (for DArk MAtter.) that is buried under the Gan Sasso mountain in Italy. According to the DAMA scientific team, a signal was detected that is consistent with dark matter, but other scientists have treated this finding with skepticism and new experiments are underway. The other possibility is a field suggested by an approach to QFT called *supersymmetry*. Either of these hypothesized fields would be sufficiently stable and interact feebly enough with normal matter to qualify. To go further into dark matter, axions, and supersymmetry is beyond the scope of this book (and its author), but I would like to quote the delightful Frank Wilczek as to the origin of the name axion:

> **I'm very fond of axions, in part because I got to name them. I used that opportunity to fulfill a dream of my youth. I'd noticed that there was a brand of laundry detergent called "Axion", which sounded to me like the name of a particle. So when theory produced a hypothetical particle that *cleaned up* a problem with an *axial* current, I sensed a cosmic convergence. The problem was to get it past the notoriously conservative editors of *Physical Review Letters*. I told them about the axial current, but not the detergent. It worked. – F. Wilczek (W2008, p. 203)**

THE GAPS

Now we will take a look at what is not covered by QFT — the gaps in the theory.

Renormalization. The most obvious gap is that QFT does not describe the interaction of a quantum with its self-field—an interaction that Richard Feynman called a "silly" idea (Chapter 6). The problem is that according to QFT the result of this interaction turns out to be infinite, which is obviously not correct. The problem was solved for EM fields by the simple expedient of replacing the infinite quantities by their experimentally-determined values. However, the fact that the infinities occur in the first place shows that something is going on at the single quantum level that is not described by the QFT equations. As we saw in Chapter 8, this problem is more serious for the gravity field because its equations do not allow for the renormalization solution.

Quantum collapse. While quantum collapse is an essential part of QFT, it is not described by the field equations. Besides this lack of theory, there are several aspects of it that bother many physicists. One is that the collapse is instantaneous and occurs at the same time at widely separated points.[8] This is especially bothersome in the case of two entangled photons. Physicists call such a process *non-local* because it involves communication faster than the speed of light. Now it is true that the field equations include a number *c* that limits the speed of propagation, but quantum collapse is not described by these equations, so there is no reason it can't occur. In fact, quantum collapse is necessary if quanta are to act as indivisible units. Since it does not lead to any paradoxes or inconsistencies, there is no reason not to accept it. In any event, non-locality has been experimentally documented. Even those who believe in particles as the ultimate reality acknowledge that something collapses.

The other problem is that, so far as we know, quantum collapse is random. QFT does not explain when or how it happens. All we know is that the probability of collapse is related to the field intensity at a given point. The idea of randomness was troubling to Einstein:

> **I find the idea quite intolerable that an electron exposed to radiation should choose, of its *own free will*, not only its moment to jump off, but also its direction. In that case, I would rather be a**

cobbler, or even an employee in a gaming house, than a physicist. – A. Einstein (letter to Max Born, 1924)

However, 25 years later Einstein softened his stand. In a 1950 speech to the International Congress of Surgeons, after describing the "overwhelming evidence" for giving up causality, he concluded by saying:

Will this credo survive forever? It seems to me a smile is the best answer. – A. Einstein (Physics Today, June 2005, p. 47-48)

While the problem of randomness is not solved by QFT, at least it has been pinned down to a specific event. It is no longer a vague phenomenon related to the role of the observer, as in QM; it is a physical event that happens with or without an observer. Maybe someday we will have a theory to describe it, but even if it is truly random there is nothing inherently contradictory about that. It may not be what we expected, but, like Einstein, we can always smile.

A speculation. Quantum collapse and renormalization both involve something that happens at the single quantum level – something not described by QFT. Renormalization is needed because QFT doesn't explain how a quantum interacts with its self-field. Quantum collapse is a mystery because QFT doesn't describe when or how a quantum transfers energy or momentum. It is possible that these two problems are related, and that if one gap is filled, the other will also be filled.

The next two gaps are not unique to QFT; they are present in every theory.

Whys and Wherefores. QFT does not explain why the numbers that appear in the equations have the values they do. The most famous example is the so-called *fine structure constant* that describes the interaction between matter fields and the EM field. This constant was once thought to have a value of 1/137, and this, as you might imagine, led to some numerological attempts to explain why nature had chosen this particular integer — and such an unusual one at that. Sir Arthur Eddington claimed that the number could be obtained by "pure deduction", but these attempts were abandoned when more precise measurements showed that the actual value is 1/137.04.

Many physicists still wonder why the masses and coupling constants are what they are, and there are attempts to find explanations that are more sophisticated than the 1/137 saga, including something called *superstring theory*. There are also less sophisticated attempts, such as the so-called *anthropic principle*, which states that if the values were different from what

they are, the human race could not exist. QFT does not supply answers, nor does any other theory. QFT does an amazing job of explaining the world we live in, but why the constants are what they are is, in my opinion, a teleological, if not theological, question.

Consciousness. Finally we come to the grand-daddy of mysteries. How dare physicists talk about "theories of everything" when they can't explain what goes on behind their very noses! But please understand, by consciousness I don't mean simple information processing, such as can be done by any computer. I mean the sense of awareness, the sensations, the feelings that human and other minds experience every day – from the color red to the beauty of a Mozart sonata or the pain of a toothache. Such sensations are known as *qualia*. Most physicists don't want to be bothered with the question, and it is left to philosophers like Charlie Chaplin to worry about it:

> **Billions of years it's taken to evolve human consciousness… The miracle of all existence… More important than anything in the whole universe. What can the stars do? Nothing but sit on their axis! And the sun, shooting flames 280,000 miles high. So what? Wasting all its natural resources. Can the sun think? Is it conscious? — C. Chaplin (film "Limelight")**

I see consciousness as a more pressing problem than the question of why the field constants have the values they do. My concern began when I was thinking about pain. Pain surely cannot be explained by fields or particles or relativity, or even quantum field theory, I thought. Nor can pleasurable sensations, like the enjoyment of music or the intense pleasure of an orgasm.

Then one day we had a visitor - a young computer hot shot. As we were sitting down for dinner I asked him "Do you think a computer can ever experience a sexual orgasm?" Well this young fellow began to tell me how you could create an orgasm by putting 0's and 1's into the right memory banks. Of course this was nonsense, so I told him he had flunked the test and couldn't have any dinner. I didn't really; we fed him, but it gave me the idea

to write a book about consciousness with the title “Do Robots Have Orgasms?” (The illustration shows the cover designed by my nephew Roger L. Brooks.) I eventually abandoned the book because I figured that a book that boiled down to one word (“no”) wouldn’t sell. However, I had already written or sketched chapters that I called “dead ends” — three explanations that have been proposed for consciousness: Artificial Intelligence, Religion, and Quantum Mechanics. As I was working on the chapter about Quantum Mechanics, I realized that all the quantum mechanical explanations ignored QFT. In fact, I became aware that QFT is ignored almost everywhere — as if it never existed. And that’s why I wrote the book that I wrote.

Is there any prospect that the consciousness mystery will ever be solved? Ambrose Bierce didn’t think so. To quote from his Devil’s Dictionary:

> **Mind, n. A mysterious form of matter secreted by the brain. Its chief activity consists in the endeavor to ascertain its own nature, the futility of the attempt being due to the fact that it has nothing but itself to know itself with. – Ambrose Bierce (B1958, p. 87)**

SUMMARY

Among physicists there are many different approaches to understanding reality. Some physicists believe that reality consists of particles, despite the many inconsistencies and absurdities, not to mention questions like what the particles are made of. Some believe in wave-particle duality, which is neither fish nor fowl (see Norsen quote on p. 4) . And others, like Steven Hawking (see quote on p. 4) don't worry about reality. As Steven Weinberg said,

> **It is truly surprising how little difference all this makes. Most physicists use quantum mechanics every day in their working lives without needing to worry about the fundamental problem of its interpretation. Being sensible people with very little time to follow up all the ideas and data in their own specialties and not having to worry about this fundamental problem, they do not worry about it. — S. Weinberg, (W1992, p. 84)**

But for those who believe there is a reality and who want to understand it, the choice was described this way by Robert Oerter:

> **Wave or particle? The answer: Both, and neither. You could think of the electron or the photon as a particle, but only if you were willing to let particles behave in the bizarre way described by Feynman: appearing again, interfering with each other and cancelling out. You could also think of it as a field, or wave, but you had to remember that the detector always registers one electron, or none — never half an electron, no matter how much the field has been split up or spread out. In the end, is the field just a calculational tool to tell you where the particle will be, or are the particles just calculational tools to tell you what the field values are? Take your pick. — R. Oerter (O2006, Chap. 6: "Feynman's Particles, Schwinger's Fields", p. 128)**

But before you take your pick, let us take a look at some of the things QFT has accomplished:

- QFT explains why the detector always register one electron or none (quanta are indivisible).
- QFT provides a simple derivation of $e = mc^2$ and gives it a meaning (both are oscillations in a field).

- QFT explains the Pauli Exclusion Principle (the spin-statistics theorem).
- QFT explains why matter quanta act like particles (the Exclusion Principle).
- QFT explains why the number of neutrons in a nucleus is limited (again, the Exclusion Principle).
- QFT explains why force fields become classical fields in the limit of many quanta (the Exclusion Principle doesn't apply).
- QFT explains the Higgs mechanism (it's another field).
- QFT offers two possible explanations for dark matter (two other fields).
- QFT explains the *subatomic zoo* ("one of the greatest scientific achievements of all time").
- QFT explains the paradoxes of special relativity (a natural consequence of the way fields behave).
- In QFT time is different from space (in accord with our natural perception).
- QFT is compatible with general relativity (although there are calculational difficulties).
- In QFT (and in general relativity) gravity is a force field, not curvature of space-time.
- QFT (and general relativity) explains gravity waves as oscillations in this field.
- QFT explains how these waves were detected (gravity-induced contraction).
- QFT explains wave-particle duality (there are no particles, there are only fields).
- QFT explains the Uncertainty Principle (fields spread out in space)
- QFT offers a solution to the measurement problem (quantum collapse).
- QFT offers an explanation of Einstein's "spooky action at a distance" (entangled quanta collapse).

Well, that's quite a list of accomplishments! With all that, you must surely wonder why QFT hasn't been accepted, if not embraced, by the physics community and the public. Well, there is a downside. To reap those benefits, we must accept that:

- Quantum fields are described mathematically by vectors in Hilbert space, not by simple numbers.
- QFT doesn't tell us how a quantum interacts with its self-field.
- QFT doesn't tell us why or when quantum collapse occurs.
- Quantum collapse is instantaneous (i.e., non-local).

And so, dear reader, I hope that, like Frank Wilczek, Steven Weinberg, Sean Caroll, Art Hobson, Julian Schwinger (and me), you will choose QFT: the only theory that offers a picture of reality that is understandable and makes sense. And perhaps one day the physics community will finally abandon the QM ship made of particles floating on a sea of paradox for smoother sailing on the seas of quantum fields.